In re. EISENBIES, et al.

Attorney Docket No. SD-8425.1

CERTIFICATION UNDER 37 CFR 1.10

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SYSTEM AND METHOD FOR REPRODUCIBLY MOUNTING AN OPTICAL ELEMENT

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SYSTEM AND METHOD FOR REPRODUCIBLY MOUNTING AN OPTICAL ELEMENT

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to prior co-pending provisional U.S. Patent Application Serial Number 60/416,159 originally filed 10/4/2002 entitled "REPEATABLE MOUNT FOR MEMS MIRROR SYSTEM" from which benefit is claimed.

STATEMENT OF GOVERNMENT INTEREST

This invention was made with Government support under government contract no. DE – AC04 – 94AL85000 awarded by the U.S. Department of Energy to Sandia Corporation. The Government has certain rights in the invention, including a paid-up license and the right, in limited circumstances, to require the owner of any patent issuing in this invention to license others on reasonable terms.

BACKGROUND OF THE INVENTION

The present invention relates to a two-piece apparatus for fixedly holding an Adaptive Optics ("AO") element in an overall optical system, wherein said AO element may be aligned with respect to said optical system and wherein said aligned AO element may be repeatedly removed and replaced in said optical system without the need for aligning said AO element.

The present invention also relates to a means for spatially aligning the AO element with six degrees of freedom.

The present invention also relates to Micro-ElectroMechanical Systems ("MEMS") and methods for aligning a deformable MEMS micro-mirror array in an optical system.

Mounting systems for use with deformable mirrors are known. See for instance, U.S. Published Patent Application Serial Number 20020097509A1, "Mounting Apparatus for a Deformable Mirror", to Graves, et al. However, descriptions of systems that provide the means for repeated replacement and

interchangeability of a deformable mirror (MEMS or otherwise) in an optical system without the need to realign the system with each interchange are not known.

Brief Description of the Drawings

FIG. 1 illustrates an exploded isometric view of the two-piece mirror holding system.

FIG. 2 illustrates a schematic cross-sectional view of one of the six contact pads and its relationship to the backplate and MEMS circuit board.

FIG. 3. illustrates an isometric view of the optical mount supporting the mirror holding system / AO element.

FIG. 4. illustrates an isometric view of the optical mount holding the mirror holding system / AO element.

Detailed Description of the Invention

An adaptive phoropter has been designed that uses deformable micro-mirror technology that provides a means to correct wave front errors caused by high order aberrations in the structures of the human eye. A design requirement for the prototype adaptive phoropter must allow repeated removal and replacement of a MEMS deformable micro-mirror within the system without the need for realignment of the system with each interchange. It is also a design requirement that multiple MEMS deformable mirrors as well as a rigid plane mirror (the alignment master) be interchangeable within the overall optical system without the need to realign the system.

In order to provide this capability, a two-piece mount, or mirror holding system **10**, shown in **FIG. 1**, was constructed for holding and aligning the MEMS deformable mirror. The mirror holding system **10** comprises a backplate **20** that mounts to and interacts with a base **30**. Backplate **20** provides a plurality of off-set members on a first surface **21** onto which any commercially available MEMS deformable micro-mirror array chip **12** and circuit board **13** (also known as the "card") may be rigidly mounted. Backplate **20** further includes three sets of six spherical contact pads **1** – **6** arranged on each of three orthogonal second, third, and fourth surfaces **22** – **24**. The six contact pads are oriented such that two sets of three pads (**1**, **2**, and **5**, and **1**, **3** and **4**) each fall along common perpendicular axes. The contact pads are further

arranged such that imaginary axes passing though the lengths of pads **1**, **4** and **5**, will intersect at a common point, as will similar imaginary axes passing though the lengths of pads **3**, and **6**. In addition, pad **1** is located on backplate **20** such that the imaginary axis passing through pad **1** also passes through the geometric center of MEMS micro-mirror array **12**.

The mirror holding system **10** is completed by mounting backplate **20** into and against base **30** and holding the two parts in place with a spring-loaded fixture (not shown) although any other equivalent means for holding these parts together including an array of magnets, an array of toggle clamps, or a cam locking assembly. Each of the six contact pads **1** – **6** interface with a corresponding adjacent hard point **31** – **36** located on three orthogonal surfaces **37** – **39** on base **30** corresponding to the three orthogonal surfaces on backplate **20**.

Mirror holding system **10** operates as follows. Shown in **FIG. 3**, base **30** is rigidly mounted in a 3-axis translational stage **50** which is itself mounted to an optical bench or "baseplate" **100** (shown in **FIG. 4**). The circuit board or card **13** carrying the MEMS micro-mirror chip **12** is installed on backplate **20** as described below in the alignment procedures, particularly procedure #7. As shown by way of representation in **FIG. 2**, each of the six contact pads is screwed into the backplate **20** with various numbers of shim stock **25** to provide for tilting and translating backplate **20** with respect to the base **30** and therefore with respect to the optical system. Shims **25** can be added or removed from under any specific pad in order to provide a known change in the angular or spatial position of the MEMS micro-mirror array chip **12** and circuit board **13**.

The adaptive phoropter is initially aligned using backplate **20** mounted with a plane mirror (not shown) installed in place of the MEMS deformable mirror and functions as a "surrogate" MEMS mirror device and serves as a master alignment fixture. Each MEMS deformable mirror backplate assembly **10** is then aligned by adjusting the shims at each contact pad until it matches the master alignment fixture. Matching the MEMS deformable mirror backplate assemblies to the pre-aligned master provides for interchangeability. Alignment procedures for using assembly **10** are detailed below.

AO SYSTEM ALIGNMENT PROCEDURE #0

SURROGATE MEMS ASSEMBLY PROCEDURE

A special fixture, hereinafter referred to as a "reticle fixture," has been created to hold a glass reticle with a grid pattern in the same location on an AO system as a MEMS device, such as micro-mirror array chip **12**. This item will represent the MEMS device and will be called the surrogate MEMS.

The surrogate MEMS will be used as the reference to which the positioning of the real MEMS devices are compared when they are mounted to the MEMS backplate **20**. This provides for interchangeability between multiple MEMS devices without the need to make compensation adjustments to other components of the AO system.

The reticle fixture (not shown) and backplate **20** will be bolted to each other to complete the surrogate MEMS assembly. The reticle is placed in the nominal position and orientation relative to the nominal positions of the contact pads **1 – 6** on backplate **20**. Each of contact pads **1 – 6** is installed on the backplate with an initial thickness of shims **25** installed under them to place them in their nominal positions.

Throughout the remainder of these procedures multiple interchangeable bases **30** and backplates **20** are utilized. However, where a particular MEMS base is used for alignment purposes it is hereinafter referred to as a "master" base **30a**.

1.) Align MEMS backplate to a traveling microscope.

- Place MEMS base master **30a** on a traveling microscope. The traveling microscope should have a digital readout for x and y position. Incident illumination should be used.
- Using the datum edges **38** and **39** of MEMS base master **30a** as references, orient the edges coincident with the axes of the microscope. This is done by tapping lightly and nudging the MEMS base master **30a** into place.
- Install backplate **20** in the MEMS base master **30a** and lock it in place with spring-loaded plungers (not shown).

- Secure the MEMS base master onto the traveling microscope.
- Translate the traveling microscope to a nominal position of the mirror normal axis and zero the traveling microscope position indicators.

2.) Install the reticle fixture and reticle on the MEMS backplate

- The reticle fixture is secured to MEMS backplate **20** through three holes using three 4-40 socket head cap screws, #4 lock washers, and #4 flat washers.
- Tighten the 4-40 screws lightly to hold the reticle fixture in place.
- Place a glass reticle (e.g. Edmund p/n A51-015) in the reticle fixture.
- Looking through the microscope, rotate the reticle in the reticle fixture until the reticle grid x and y axes are angularly aligned with backplate **20** edges (already assembled onto base master **30a** itself on translation stage **50**). Secure reticle position with a fast-setting epoxy.
- Looking through the microscope, nudge or tap the reticle fixture relative to backplate **20** to center the reticle coincident with MEMS device normal axis (already aligned with the microscope axis).
- Double-check the angular orientation of the reticle, making any fine adjustments as needed.
- Tighten the mounting screws for the reticle fixture.
- Recheck the orientation and position of the reticle grid in the microscope.
- There should be no need to make adjustments to the tilt or axial position of the reticle at this time. (These parameters will be accommodated by the positioning of the optics on baseplate **100**.)
- Remove and replace the surrogate MEMS to verify repeatable positioning of the reticle grid in MEMS base master **30** while it is still installed on the microscope. Ensure that the six contact pads on the surrogate MEMS are in contact with MEMS base master **30**.

AO System Alignment Procedure #1

Establishing the MEMS micro-mirror normal axis

Before placement of the deformable mirror and system optics, it is necessary to define the position of the normal axis of the MEMS device on baseplate **100**. The normal axis will be represented by a laser beam set up in the following procedure.

A laser (not shown) is mounted on baseplate **100** having adjustment in x and y translation, and tilt adjustment in pitch and yaw.

The axis will be defined by two known points located on baseplate **100** using specially made alignment targets.

Each target is L shaped, wherein the horizontal portion or "base" sits at datum locations on the surface of baseplate **100**, and wherein the vertical portion of the L-shaped target includes a small aperture at the desired beam height above the surface of baseplate **100**. When used on baseplate **100** of the present AO system, a pair of 5/16" Ø shoulder screws are in specific locations on baseplate **100** to place and orient the target into position. This will hold the aperture on the target at a point 3" directly above the surface baseplate **100** and coincident with the direction of the axis.

1) Define the location of the center of the deformable mirror surface

- Install the target on an assigned first datum hole located on baseplate **100** by placing the bore of the first target on the assigned datum hole and secure it with shoulder bolts. This datum hole defines the location of the deformable mirror surface as it will be placed on baseplate **100**.
- The location of the small aperture at the 3" beam height on the target is designated as the nominal location of the target in the x, y, and z position.

2.) Define a second endpoint for the nominal mirror normal axis.

- A second target is set at the opposite end of baseplate **100**. This target will be used to define the opposite end of the normal axis.
- Place the second target on baseplate **100** in the same orientation as the first target located at the position of the MEMS micro-mirror device.

- Locate the second target using two shoulder screws so that the aperture on the second target is coincident with the other end of the nominal normal axis.
- The location of the hole at the 3" beam height defines the second point on the normal axis in x and y position.

3.) Set up a laser beam on the normal axis defined by the two targets.

The line passing through the aperture on each target corresponds to the nominal location of the normal axis of the deformable micro-mirror array **12**. A laser beam will be set up that goes through the two apertures on the targets to complete the definition of the MEMS device normal axis on baseplate **100**.

- Mount a laser beyond the second target so that its beam points in the direction of both targets. The laser should have a mount that provides pitch and yaw tilt adjustments, as well as the capability to translate the beam in the x and y directions. The closer the laser is mounted to the second target, the better.
- Using the translation adjustments of the laser mount, bring the laser spot into the aperture of the second target.
- Remove the second target, and using the tilt adjustments of the laser mount, bring the laser spot into the aperture of the first target.
- Replace the second target and use the laser mount translation adjustments to again bring the laser spot into the aperture of the second target.
- Repeat the prior two steps until no further iterations are necessary.

The laser beam is now coincident with the normal axis of the MEMS micro-mirror device.

The target positioned at the location of the MEMS device should not be removed before continuing to the next step.

AO SYSTEM ALIGNMENT PROCEDURE #2

PROCEDURE FOR SETTING THE POSITION AND ORIENTATION OF A MASTER RETICLE

At this stage a surrogate MEMS assembly will have been assembled in procedure #0 and a normal axis for the MEMS micro-mirror will have been defined on baseplate **100** by alignment procedure #1.

Multiple MEMS micro-mirror assemblies and a surrogate MEMS assembly will be interchangeable in the AO microscope system without the need for adjustments to the alignment. MEMS devices and their mount assemblies will be aligned using baseplate **100** to match the surrogate MEMS, consisting of a grid reticle and an identical interface to the MEMS mount.

1.) Install the MEMS Translator Assembly on the baseplate

- Attach base **30** to the MEMS translator assembly **50**.
- Install the MEMS translator assembly on baseplate **100**.

A mounting system is provided in the MEMS translator assembly **50** that locks backplate **20** holding deformable micro-mirror array **12** or surrogate MEMS in place on base **30**. Translator assembly **50** provides course positional adjustments of the MEMS micro-mirror device in the transverse directions parallel to the surface of baseplate **100**, and for pitch angular adjustments. The interface between the deformable micro-mirror mount assembly (backplate subassembly) and base **30** allows fine adjustment in six degrees of freedom through the placement of shims strategically placed beneath the contact pads.

2.) Transfer the reference for the position of the MEMS device into the focal plane of a CCD camera

The nominal position of the MEMS device is at a point 3 inches above the master hole on baseplate **100**, as identified previously in procedure #1. A pair of alignment targets each having a small aperture at a 3" beam height remain in place in baseplate **100** following alignment procedure #1. The two target apertures define the nominal location of a normal axis at the center of the MEMS micro-mirror. Furthermore, the surface of the first target corresponds to the nominal plane position

and orientation of the MEMS micro-mirror device, and the small aperture on the target corresponds to the x and y center position of the mirror.

- Install a CCD camera on baseplate **100** facing in the direction of the MEMS translator **50**. Use a camera mount that can be repeatedly replaced on baseplate **100**.
- Bring an image of the aperture and the surface of the first target into focus in with the CCD camera. This redefines the axis and x and y reference for the MEMS micro-mirror device to the focal plane of the camera.
- Secure the position of the camera.
- Note the x and y position of the first target aperture by marking the image of the center position of the reticle grid on the camera display using a marking stylus.
- Remove and replace the camera to verify that it can be repeatedly replaced on baseplate **100** and return the x-y position of the first target aperture to its prior position in the focal plane of the camera.
- Remove the first target from baseplate **100**.

3.) Installation and initial alignment of the surrogate MEMS

- Insert the surrogate MEMS/backplate assembly into base **30** on MEMS translator assembly **50**. Lock surrogate MEMS into place making sure that all six contact pads are in contact with their respective hard points on base **30**.
- Using the linear slides on MEMS translator assembly **50**, bring the center of the grid on the surrogate MEMS onto the x-y center defined on the CCD display.
- Remove the CCD camera and allow the normal laser to reflect off the reticle surface.
- Adjust the pitch angle of the reticle with the tilt stage on MEMS translator assembly **50** until the reflected beam is at the same height as the beam emitted from the laser.

- Replace the CCD camera and reposition the surrogate MEMS in x and y as needed, as this may have changed when adjusting the pitch angle.
- Verify the surface of the grid is in focus and adjust as needed.
- Recheck x and y position by repeating the prior two steps.
- Remove the CCD camera and verify the incident and reflected beam from the surrogate MEMS are still coincident.
- Lock stage on MEMS translator assembly **50**.
- Remove the surrogate MEMS and replace.
- Again, verify x, y, and z position.
- Remove CCD camera and verify incident and reflected beams are coincident. If not, reevaluate alignment.

If everything is in position, then the nominal position of the surrogate MEMS has been established and the surrogate MEMS master has been aligned to a "nominal" reference orientation on baseplate **100**. From this point the surrogate MEMS should be handled with care. Be prepared to use the CCD camera in following steps.

AO SYSTEM ALIGNMENT PROCEDURE #7

MATCHING A MEMS DEVICE TO THE SURROGATE MEMS

In order to adapt the AO system to a functional wave front correcting system, the surrogate MEMS (an optically flat glass microscope reticle) is replaced with an operational MEMS device comprising a deformable micro-mirror array "chip" (hereinafter referred to as a micro-deformable mirror or "MDM).

At the start of the procedure, an identical backplate **20** as that used at the beginning of procedure #0 is prepared. Each of its six contact pads **1 – 6** will have an initial thickness comprising multiple shims installed between themselves and surfaces **22 – 24** of backplate **20**. The number of shims under each pad will be adjusted to orient and position each MDM mounted on any given backplate, relative to its six points of contact with a given base **30**, identical to that of the surrogate MEMS relative to its same six points of contact.

In procedure #0, we described the positioning of the MEMS in x, y, and z-theta. In addition, this procedure will describe matching the position in z, x-theta, and y-theta.

1.) Mounting the MDM system onto a backplate

This part of the procedure is similar to the procedure used wherein the reticle fixture is attached to its backplate.

- The MEMS base master **30** is first set up on a traveling microscope.
  - Fix the MEMS base master to the traveling microscope.
  - Place the surrogate MEMS in the MEMS base master and lock down.
  - Bring the reticle grid into focus in the focal plane of the traveling microscope and nudge the MEMS base master until the grid is aligned in z-theta to the traveling microscope translation stages.
  - Translate the traveling microscope to the center of the surrogate MEMS grid and zero the scales.
- Install six contact pads on one of a backplate **20** with the nominal initial thickness of shim stock at each pad.
- Install an MDM card on backplate **20**. At each mounting hole, place 1/8" thick spacers between card **13** and backplate **20**. Place card **13** onto backplate **20**. Insert a #4 washer, a #4 lock washer, over a 4-40 x ½" long screw into each mount hole on of card **13** in order to hold it in place. Snug the screws just enough to hold the card. The screws will be fully tightened later.
- Remove the surrogate MEMS from the MEMS base master
- Place the MEMS backplate/card assembly in the MEMS base master **30** and lock into place.
- Install the MDM in the zip socket and lock into place.
- Bring the surface of the MDM into focus with the microscope (z-position adjustment of backplate **20** will be completed later)
- Nudge card **13** on backplate **20** until the center of the MDM corresponds to the zero position and orientation of the traveling microscope.

- Tighten the 4-40 screws.

In the configuration shown, the sensitivity of the three translation adjustments is 1:1. For every 0.001" of shim thickness added to pad **2**, backplate **20** will rotate 333 micro-radians in the positive x-theta direction and experience an Abbe error of 0.0006" in the negative y-direction. For every .001" of shim thickness added to pad **3**, backplate **20** will rotate 457 micro-radians in the positive y-theta direction and experience an Abbe error of 0.0008" in the positive x-direction. For every 0.001" of shim thickness removed from pad **6**, backplate **20** will rotate 457 micro radians in the positive z-theta direction.

Since x-theta and y-theta are completed first, and x and y translation later, it would be redundant to attempt to correct for the translation coupling. However, if after we set all the pads we find that the tilt is off, it will be useful to take these effects into consideration to minimize the number of steps needed.

2.) Matching the MDM to the surrogate MEMS in X and Y-theta

- Fixture the MEMS base master onto a (white light) interferometer system with the surrogate MEMS installed.
- Mount the MEMS base master so that the transverse axes of the surrogate MEMS reticle is parallel to the interferometer (concentric circular fringes).
- Remove the surrogate MEMS from the MEMS base master and install a MDM/backplate assembly.
- Look at the fringes and add/remove shims under pads **2** and **3** until surfaces are parallel (concentric fringes).

3.) Centering and orienting the MDM

- Place the surrogate MEMS micro-mirror device on the traveling microscope and align to its axes.
- Remove the surrogate MEMS and place the MDM/backplate assembly in the MEMS base master.
- Translate the traveling microscope to the center of the MDM and note the orientation.

- Remove the MDM/backplate assembly and add or remove shims needed to orient the MDM in z-theta.
- Replace the assembly and repeat until the MDM is oriented.
- Move the traveling microscope to the center of the MDM surface.
- Note the new position on the traveling microscope scales.
- Remove the assembly and add or remove shims to center the MDM relative to the traveling microscope.
- Return the traveling microscope to its zero position.
- Replace the MDM assembly and confirm it is centered and oriented. If not, iterate the steps again.
- Cross check with surrogate MEMS.

4.) Confirmation of alignment

After all alignment steps are completed, review and repeat as required all the foregoing procedural steps to confirm the MDM/backplate assembly matches the surrogate MEMS.